

Beam Diffraction by a Planar Grid Structure at 93 GHz

Moonil Kim,* Robert M. Weikle, II, Jonathan B. Hacker,
David B. Rutledge

Division of Engineering and Applied Science
California Institute of Technology
Pasadena, CA 91125

INTRODUCTION

The idea of using diode grids for electronic beam steering was introduced by Lam *et al* [1]. As shown in Figure 1, when an incident beam reflects off the diode grid, the direction of the reflected wave can be controlled by progressively varying the reflection phase across the grid. The reflection phase of the diode grid can be controlled by varying the DC bias on the diodes. Later, a monolithic diode grid was fabricated with 1600 varactor diodes, and a relative phase shift of 70° at 93 GHz was measured [2]. This work verified the transmission-line theory used to design the grid, but the phase shift was not sufficient to steer the beam. Recently, Johansson [3] designed and built a passive planar grating-reflector antenna that focused a beam. A rigorous moment-method solution was applied to choose a grating geometry to select the first-order diffracted wave. In this work, using the transmission-line model approach, the goal was to demonstrate that the beam can be steered by building a grid structure without diodes to give a fixed beam shift. In these grids, diodes were replaced by gaps with different sizes to obtain different capacitances needed to steer a beam at 93 GHz. The result show a successful beam shift of 30° with a loss of 2.5 dB.

THEORY

If the wave has different incident and reflected angles, the characteristic impedance of the incident wave and the reflected wave are different. The formulas for the reflection coefficient are different for the E and the H field,

$$\rho_e = \frac{Y_i - Y_r}{Y_r + Y} \quad \text{and} \quad \rho_h = \frac{Z_i - Z}{Z_r + Z} \quad (1)$$

where Z_i and Z_r are the characteristic impedance of the incident wave and reflected wave, and Z is the impedance of the grid. Y_i , Y_r , and Y are the inverses of Z_i , Z_r , and Z ,

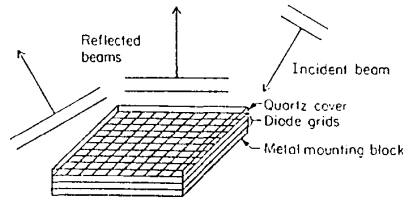


Figure 1 Electronically programmable beam-steering array proposed by Lam *et al* [1].

respectively. When Z is purely imaginary, we can write $Z = jX$, and the phase of the two reflection coefficients differ by a constant, π . In order to steer the beam, the phase of the reflection coefficient for the grid should vary linearly across the grid as

$$\angle \rho = -k_g x \quad (2)$$

where x is the distance across the grid, and k_g is a constant. The incident beam will have a variation across the grid of $\exp(-jk_i x)$, where $k_i = k_0 \sin \theta_i$. In this formula, k_0 is the free space propagation constant, and θ_i is the incident angle. The reflected wave will have a corresponding variation of $\exp(-jk_r x)$ where $k_r = k_0 \sin \theta_r$, and θ_r is the reflected angle. We can then write

$$k_g = k_r - k_i \quad (3)$$

For given incident and reflected angles, the grid reactance must satisfy

$$k_g x = \tan^{-1} \left(\frac{X(x)}{Z_i} \right) + \tan^{-1} \left(\frac{X(x)}{Z_r} \right) \quad (4)$$

The required is plotted in Figure 2b as a dashed line for an incident angle of 30° and a reflected angle of 0° for waves incident with TM polarization. This figure shows that both very large and very small reactances are required to steer the beam. This is difficult for a single grid. However, we can reduce the required reactance range by stacking two identical grids (Figure 2a). If the grids are surrounded by substrates with a high dielectric constant, the wave inside the substrates could be approximated by a TEM wave at normal incidence. The reactance of each grid then can be transformed to the required total surface reactance using the transmission-line model as,

$$X(x) = X_g(x) - \frac{\eta_d^2}{X_g(x)} \quad (5)$$

where η_d is the characteristic impedance of the dielectric substrate used. The required range for $X_g(x)$ is then reduced to $0.6\eta_0$, where η_0 is the free space characteristic impedance (Figure 2b).

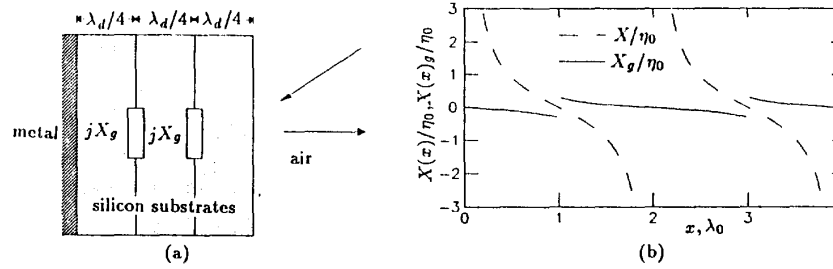


Figure 2 (a) Side view of two-layer stack with variable shunt elements. (b) The total reactance required to shift beam 30° (dashed line) and for a grid in a two-layer stack (solid line).

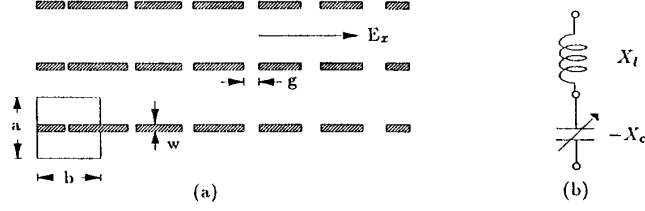


Figure 3 (a) A drawing of a grid with varying gaps. The area enclosed by the rectangle shows a unit cell. (c) The resulting equivalent circuit.

To determine the shunt reactance produced by a single grid, it is convenient to assume that the grid parameters vary slowly, and to define a unit cell. For a TEM wave, electric walls can be placed anywhere along the direction of H field and magnetic walls along the E field. A unit cell is then defined as the area enclosed by lines that connect the middle points between gaps (Figure 3a). After placing electric walls on the sides and magnetic walls on the top and bottom of the unit cell, the inductive reactance due to the metallic lead can be found using the method developed by Eisenhart and Kalin [4],

$$X_l(w) = \frac{b}{a} \omega \mu \sum_{m=1}^{\infty} \frac{1}{\alpha_z} \text{sinc}^2 \left(\frac{m\pi w}{a} \right) \left(1 - \frac{w}{a} \right) \quad (6)$$

Assuming that the inductance can be chosen as the average of the varying capacitive reactance, the minimum capacitance required should be smaller than $\frac{1}{2\pi f \Delta X_g}$, which is about 7 fF at 93 GHz. This kind of capacitance is too small for packaged varactor diodes. Unless the grid is made monolithically, frequency of operation has to be lowered or several diodes should be placed in series. For the passive grid without diodes, the capacitive reactance produced by the gap can be obtained using Eisenhart and Khan method [4],

$$X_c(g) = -\frac{b}{4a} \omega \mu \sum_{m=0}^{\infty} \frac{\epsilon_{0m} \text{sinc}^2 \left(\frac{m\pi w}{a} \right) \left(1 - \frac{w}{a} \right)}{\sum_{n=1}^{\infty} \text{sinc}^2 \left(\frac{n\pi g}{b} \right) \frac{\alpha_z k^2}{k_y^2 - k^2} \left(1 - \frac{g}{b} \right)} \quad (7)$$

The capacitance given by the formula can easily be small enough to allow the required $0.6\eta_0$ reactance change at 93 GHz.

EXPERIMENTAL RESULTS

A two-layer grid was built at 93 GHz on 600 Ω -cm silicon substrates. The metal strips are gold, and are 200 nm thick. The patterns were made by lift-off. The size of the unit cell was chosen to be $\lambda/5$, and the total grid size was 4λ by 4λ . Figure 4(a) shows how the experiment was set up. Once the data was taken, the grid was replaced by a mirror of the same size to compare the results. The beam off the grid was shifted 30° from the beam off the mirror. The loss is 2.5 dB. At the same time, the zero-order beam has been reduced by 8 dB.

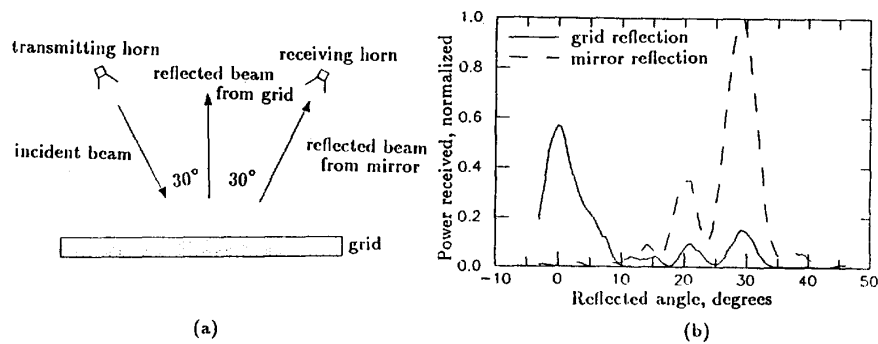


Figure 4 (a) The experimental scheme, and (b) the results.

CONCLUSION

Planar grid structure shifted the beam direction 30° with 2.5 dB loss at 93 GHz. Here, a simple transmission-line model was used to convert the zero-order diffracted wave to the first order. This model is useful because it can easily include semiconductor devices with biasing circuits. In addition, this kind of planar structures can be integrated together with other active grid structures, such as oscillators [5] and mixers [6] to form a complete millimeter-wave system.

ACKNOWLEDGEMENTS

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